SUMMARY REPORT

for

MULTIPLE·IMAGE INTEGRATION PRINTER

SECTION I - SUMMARY

SECTION II - RECOMMENDATIONS

19 January 1967

This report has been prepared to summarize the various documents submitted under the program entitled 'Multiple Image Integration Printer' and to present recommendations for the continuation of the program in a direction consistant with the general solution of the image integration problem.

The documents previously submitted and summarized in Section I are listed below in chronological order.

December 1965 - Phase I - Feasibility Study Multiple-Image Integration Viewer - Printer

STAT

April 1966 - Supplement to [redacted] Interim Report

August 1966 - Proposed Change of Scope for Multiple Image Integration Study

October 1966 - Design Plan for Phase II - Multiple Image Integration Printer

STAT

Section II contains [redacted] recommendations for the continuation of this program and is presented as a change of scope proposal as it approaches the problem of image integration in a manner different than the method originally proposed.

SECTION I

MULTIPLE IMAGE INTEGRATION PRINTER SUMMARY

19 January 1967

LIST OF FIGURES

1.0 INTRODUCTION

Image integration is the technique of combining several images of the same area in order to improve image contrast or resolution. Optical image integration has been previously investigated at [redacted] using three cameras STAT from which three photographs were obtained from the same vantage point at the same instant. These three films were then added optically in a special enlarger. It was found that the contrast of low contrast detail was improved, and that negatives exposed on a relatively coarse grained film yielded an integrated print similar to that from a finer grained film. The improvement obtained was not as great as expected, however, and fell short of theoretical predictions.

The present program was initiated to investigate the application of an electronic viewing system to image integration. This approach allows considerable flexibility in image processing, and also allows films taken on different missions from different vantage points to be integrated, using automatic image registration techniques. Image integration, using an optical distortion correction system, is also a possibility.

While the original intent was to use an ARES Viewer as a means of testing the feasibility of these ideas, it was soon realized that the amount of pictorial information presented in a visual display, using 500 image elements across the diagonal, was quite inadequate for photo interpretation. The emphasis was therefore transferred to a slow-scan printout giving 3000 line resolution on to a hard copy.

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2.0 OBJECTIVES

The objectives of this study were: (1) to investigate theoretically the benefits to be obtained by image integration as an aid to photo interpretation, (2) to develop the techniques required for a practical system for the integration of multiple image of different geometry, using an electronic viewing system with automatic image registration.

Among the factors investigated theoretically were:

Registration Accuracy Requirements

Effect of Second Order Distortions

Signal-to-Noise Ratio Improvement

Weighting Factors for Multiple Images

Modulation Transfer Functions for the Integrated Image

Design studies were made in the following areas:

Control of Gamma (Tone Reproduction)

Shadow Suppression

Scanning Systems, Flying Spot and Image Dissector

Superimposition Techniques

High Resolution Slow-Scan Printout

3.0 SYSTEM ANALYSIS

3.1 System Models

Before describing the theoretical work, some system models for high-resolution photography will be described.

Figure 1 shows two photo interpreting systems presently in use for the detailed examination of high-resolution photography. In Figure 1 a contact print is made of the original negative on high resolution duplicating film, and this positive copy is viewed with a microscope at varying powers of magnification. Some loss of resolution and contrast occurs in this process, but this can be minimized by the use of a good printer and high resolution dupe stock.

In Figure 2 the negative is enlarged optically onto a print or transparency which can be viewed directly or with a hand magnifier. The main loss in this process is due to the enlarging lens.

Figure 3 shows the model for an optical image integration in which a number of inputs, N are added to give a simple print. Again, information is lost due to the MTF of the enlarging lenses, but other serious disturbing factors are also present, such as misalignment of images and uncorrected distortion due to the camera system and viewpoint.

An electronic image integration system is shown in Figure 4. The inputs are scanned, converted to electrical signals, combined and then displayed on a cathode ray tube which prints out onto the output film. The output image is degraded here by the MTF's of each component, and in addition to the disturbing factors of image misalignment and distortion, a further degradation due to electrical noise enters the picture.

3.2 Signal-to-Noise Ratio

The only justification for using the multiple-input systems of Figures 3 and 4 is that they provide more information than the single input systems of

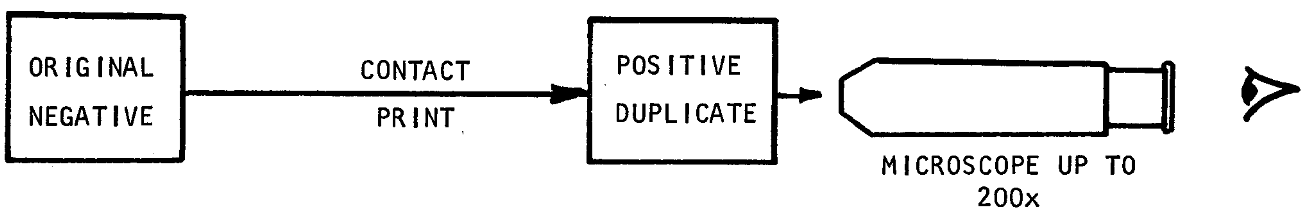

FIGURE 1 - CONTACT PRINT

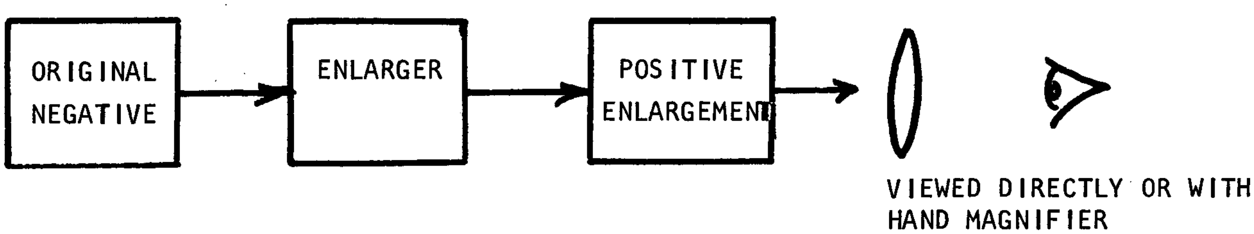

FIGURE 2 - ENLARGEMENT

METHOD OF EXAMINING DETAIL IN HIGH RESOLUTION PHOTOGRAPHY

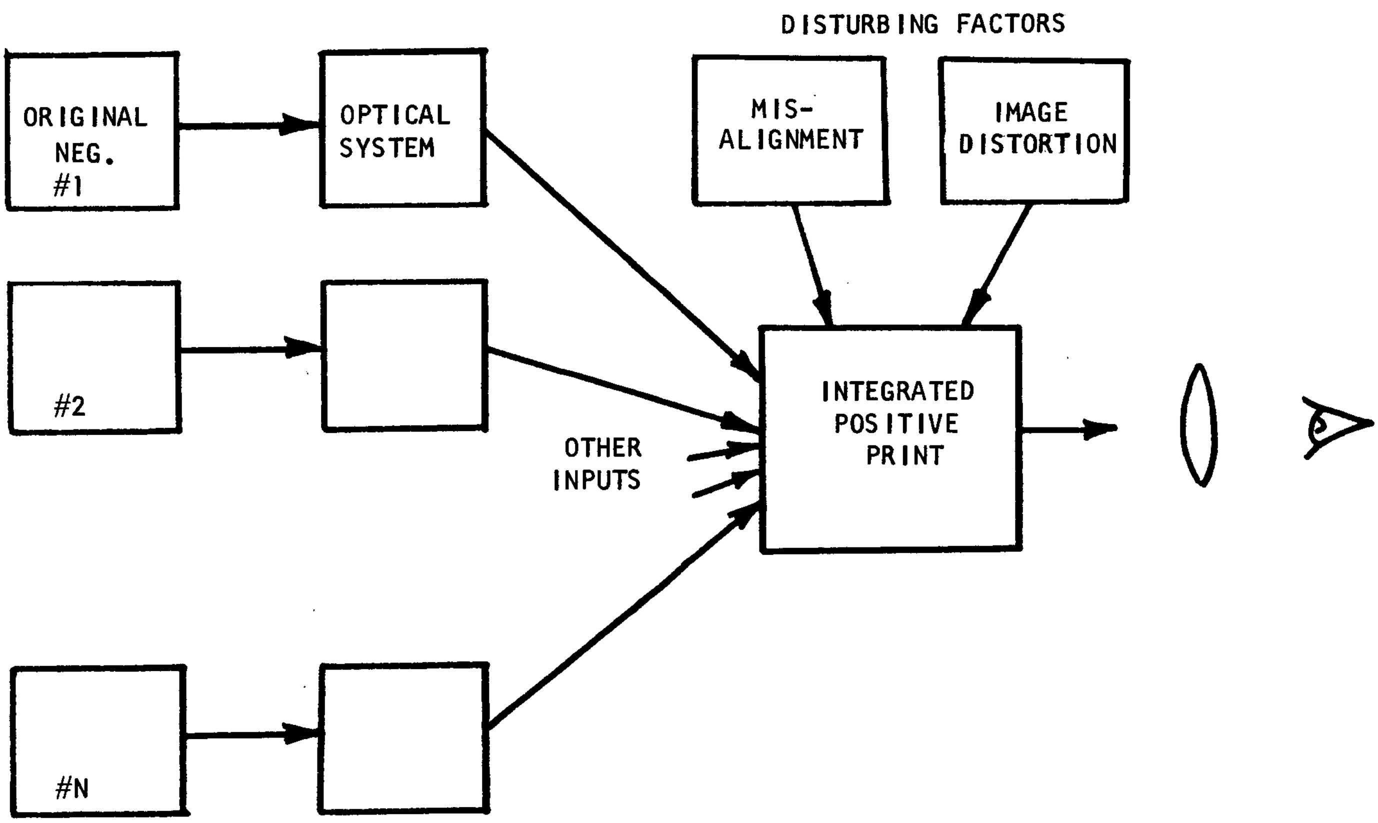

FIGURE 3

OPTICAL IMAGE INTEGRATION SYSTEM

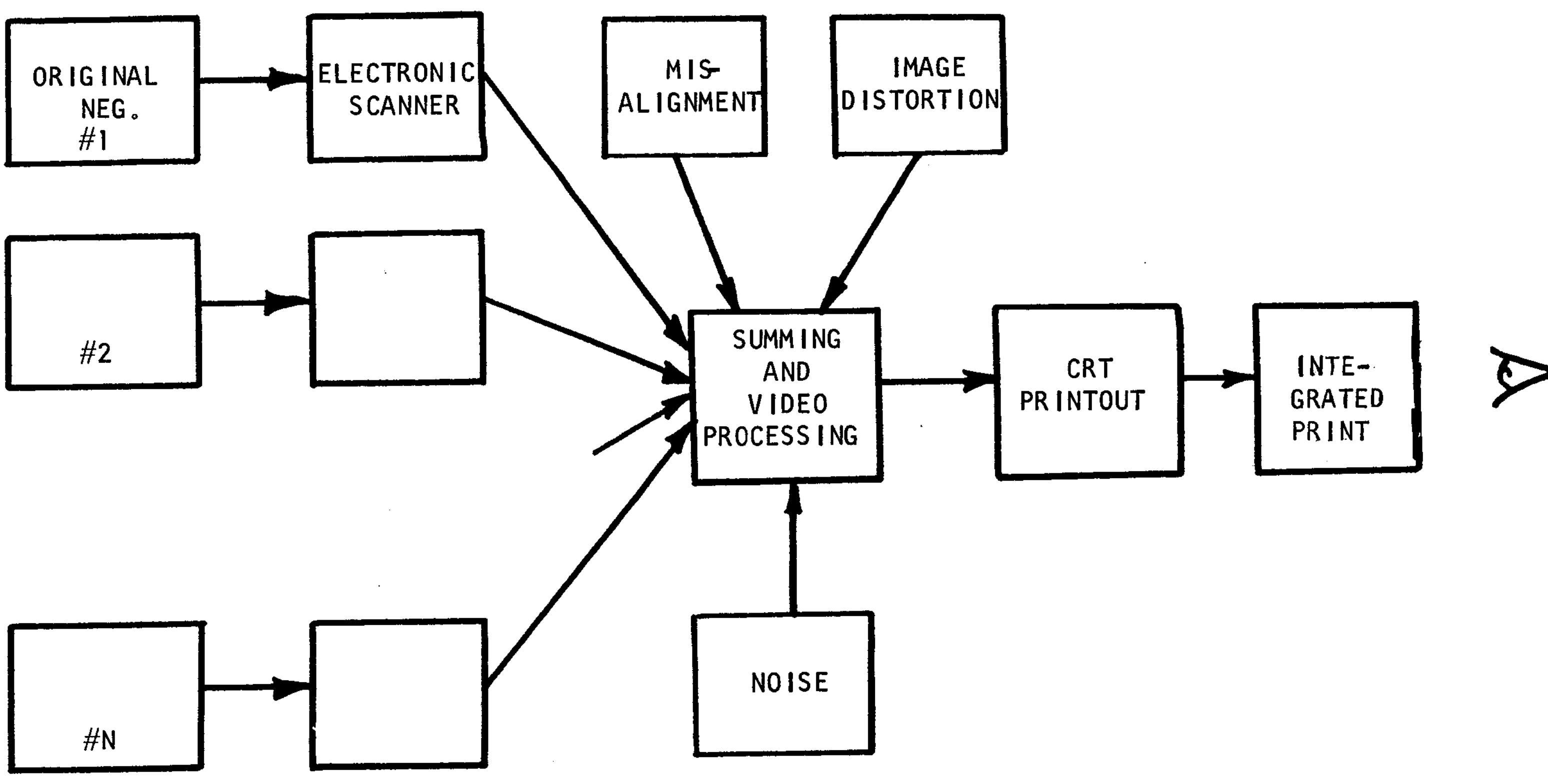

FIGURE 4

ELECTRONIC IMAGE INTEGRATION SYSTEM

Figures 1 and 2. If we assume ideal conditions (no losses due to misalignment, etc.) then it can be shown that if N separate images of the same scene, each of the same signal-to-noise ratio are integrated, then the signal-to-noise ratio of the output is increased by the factor $\sqrt{N}$. Furthermore, if the signal-to-noise ratios of the inputs are different, and they are weighted in proportion to their S/N ratios before integration, then the signal-to-noise ratio of the output cannot be degraded by any input.

If an input has zero signal content, it is added with zero weight. There is no theoretical limit to the number and quality of the inputs to be integrated, but the improvement obtained gets smaller with each additional input. Of course, there is a practical difficulty in measuring the signal-to-noise ratios of the various inputs.

The general expression for the resultant amplitude signal-to-noise ratio for N inputs is:

$$R = K \left[\sum_{i=1}^{n} \frac{a_i^2}{\sigma_i^2} \right]^{\frac{1}{2}}$$

Where a_i is the signal amplitude of the ith input

σ_i is the noise variance of the ith input

K is a constant

In the case of equal input signal amplitudes and equal noise variances,

$$R = K \sqrt{N} \cdot \frac{a}{\sigma}$$

The noise variance of an emulsion, σ, is termed the RMS granularity. The equation shows that when N inputs of equal granularity are integrated, the resultant granularity drops to $\sigma/\sqrt{N}$.

3.3 Emulsion Threshold Functions

The effect of image integration can be best understood by reference to the emulsion threshold functions. These functions, which are obtained experimentally for each type of film emulsion, specify the amount of incident modulation that is required on the film in order to resolve 3-bar patterns of various wavelengths. The values used here are taken from STAT

STAT

Figure 5 shows a typical case. The incident modulation depends on the scene contrast, atmospheric haze, and the modulation transfer function of the camera lens, and drops at high modulation frequencies. The emulsion threshold rises at high modulation frequencies, indicating that greater image modulation is required in order to resolve detail at higher frequencies. The point at which the incident modulation curve intersects the emulsion threshold curve gives the visual resolving power of the system. The vertical distance between the two curves is a measure of the visual signal-to-noise ratio of the photograph. The height of the emulsion threshold is proportional to the RMS granularity of the film, $\sigma(D)$. When a number of films N, is integrated, the effect is to reduce the resultant granularity by a factor $1/\sqrt{N}$. The emulsion threshold is then lowered resulting in the resolving power being increased from R_1 to R_2 and a greater signal-to-noise ratio. It may appear at first as though unlimited improvement were possible, but the improvement actually obtainable is limited by several factors listed below.

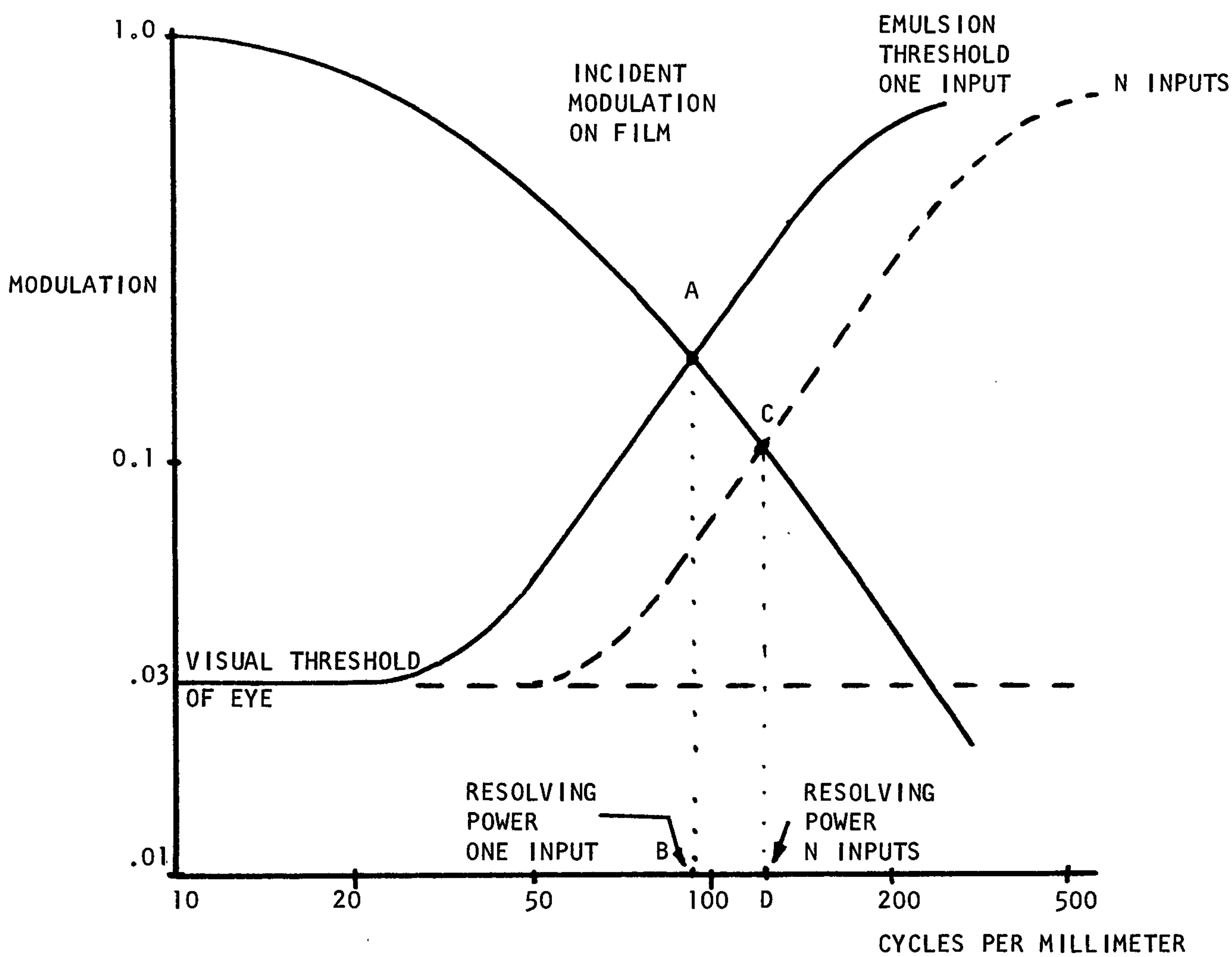

FIGURE 5

EMULSION THRESHOLD FUNCTIONS

(1) The visual threshold - this is the minimum image modulation that can be detected by the human eye.

(2) The modulation transfer function of the image integration system, which may reduce the modulation below the visual threshold.

(3) Misalignment or distortion of the image which may reduce the transfer function.

(4) Electrical noise introduced by an electronic image integration system, which adds to the granularity of the film.

These factors can completely negate any advantage obtained from image integration, so it is necessary to evaluate these effects quantitatively.

3.4 Visual Threshold

The visual threshold is,of course, subject to variation from person to person, and is generally quoted as between 2 and 3 percent. A value of 2-1/2 percent will be used in the present case. This value of modulation pertains to the viewed image, which in the systems considered, is a positive print or transparency on duplicating stock.

The visual threshold must be referred back to the original negative in order to determine whether or not detail will be obscured by granularity. For small values of modulation, the modulation on the positive print is given by $M_2 = \gamma_2 \cdot M_1$ where γ_2 is the gamma of the duplicating stock and M_1 is the modulation on the original negative. The visual threshold can then be determined for any value of γ_2.

3.5 Modulation Transfer Functions

The modulation transfer functions of the various components, such as lenses and films, have been measured in the laboratory and are available for most items. Some MTF's that will be used in evaluation of various image integration systems are shown in Figure 6. Emphasis has been placed on using the highest resolution components and films except for Type 4401, a fast, relatively grainy film which is used as an example in the film limited system. The effects of image motion and atmospheric turbulence have been neglected. A high contrast 3-bar target is used as an object because emulsion threshold functions are available only for this type of object. It is realized that the MTF's of the lenses employed will be different for square wave targets than for sine waves. However, this is justified in view of the approximate nature of the performance predictions. As discussed later, a definitive evaluation of image integration requires more experimental work.

3.6 Misalignment Error

If two sine wave images are considered, and if they are displaced by 90° or 1/4 wavelength of their spatial frequency, the resultant amplitude of the combined image falls to 0.7. A useful criterion for misregistration therefore is that the displacement error should not exceed 1/4 wavelength of the highest usable spatial frequency on the film, which is generally taken as the frequency at which the modulation has fallen to 3%. On this basis the following requirements for registration accuracy are obtained:

System Resolution at 3% Response Lines Per Millimeter	Maximum Displacement Error, Microns
50	5.0
100	2.5
150	1.7
200	1.25

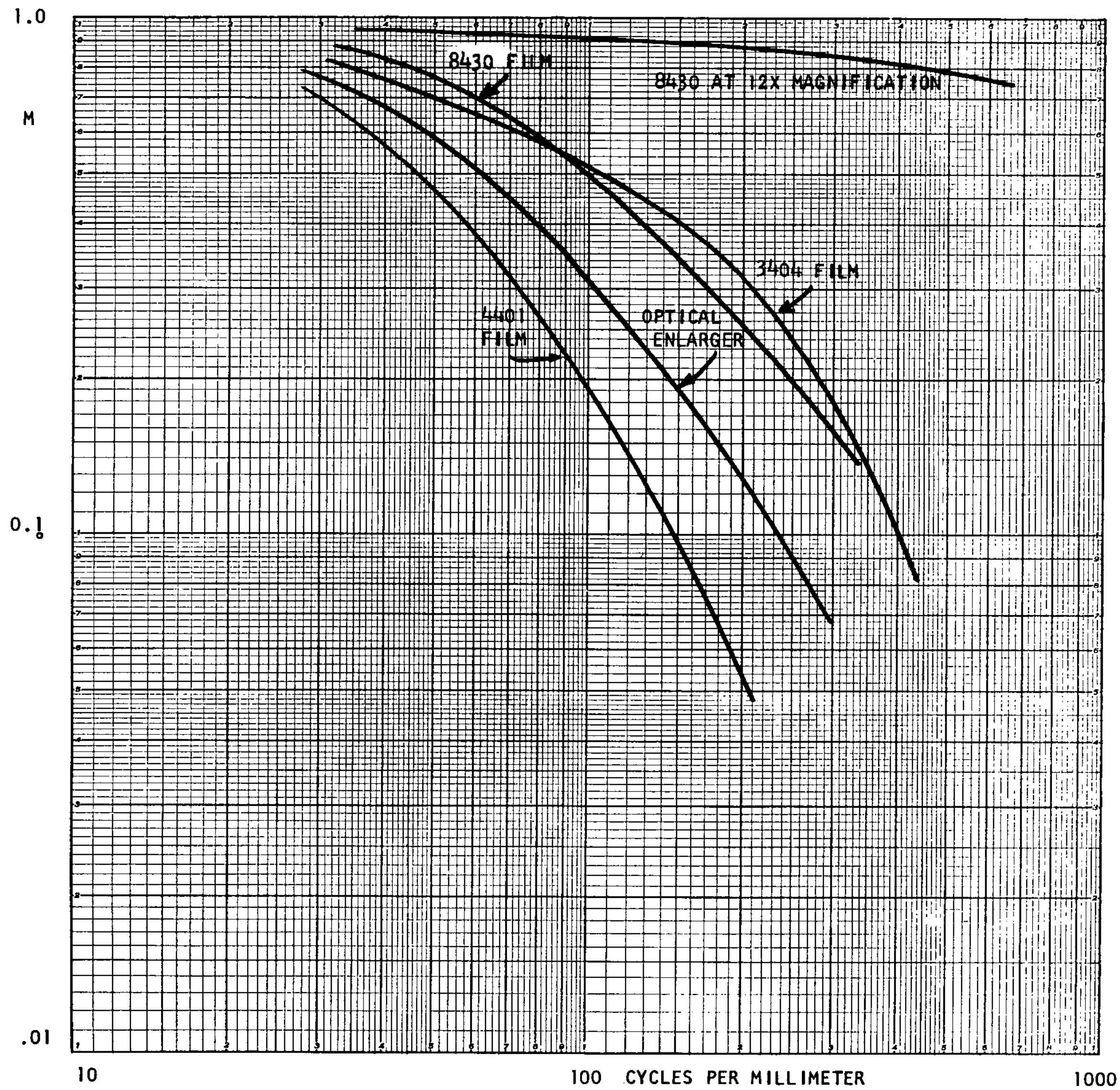

FIGURE 6

MODULATION TRANSFER FUNCTIONS

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MISALIGNMENT ERROR

System Resolution at 3% Response Lines Per Millimeter	Maximum Displacement Error, Microns
50	5.0
100	2.5
150	1.7
200	1.25

To determine the registration accuracy required for an enlarged print, these figures should be multiplied by the enlargement ratio

Second Order Distortion

Lens Focal Length, Inches	Relative Tilt Angle 45°	Relative Tilt Angle 15°
6	1.5mm	2.4mm
12	2.0	3.5
24	3.0	4.8
48	4.1	7.0

FIGURE 6A - RESOLUTION/DISPLACEMENT & SECOND ORDER

To determine the registration accuracy required for an enlarged print, these figures should be multiplied by the enlargement ratio.

3.7 Second Order Distortion

Second order distortion is produced when the camera film plane is not parallel to the surface of the ground, and can be due to camera tilt, terrain slope, or a combination of both.

Image displacements due to second order distortion were computed for camera systems of focal length between 6 inches and 200 inches at tilt angles of 7.5° to 45°.

Assuming a system resolution of 200 lines per millimeter, it was found that correction of second order distortion would be required when image diameters larger than those indicated in the table below are to be integrated.

Lens Focal Length Inches	Relative Tilt Angle 45°	Relative Tilt Angle 15°
6	1.5mm	2.4mm
12	2.0	3.5
24	3.0	4.8
48	4.1	7.0

The conclusion reached is that second order correction would be necessary if the areas integrated were commensurate with normal viewing fields. However, at the magnifications necessary to obtain improvement with image integration, the field of view would not exceed these values.

4.0 OPTICAL IMAGE INTEGRATION

Figure 7 shows the performance of a system employing a high quality aerial camera lens, the [redacted] f3.5 24-inch Petzval, and using Type 4401 film.

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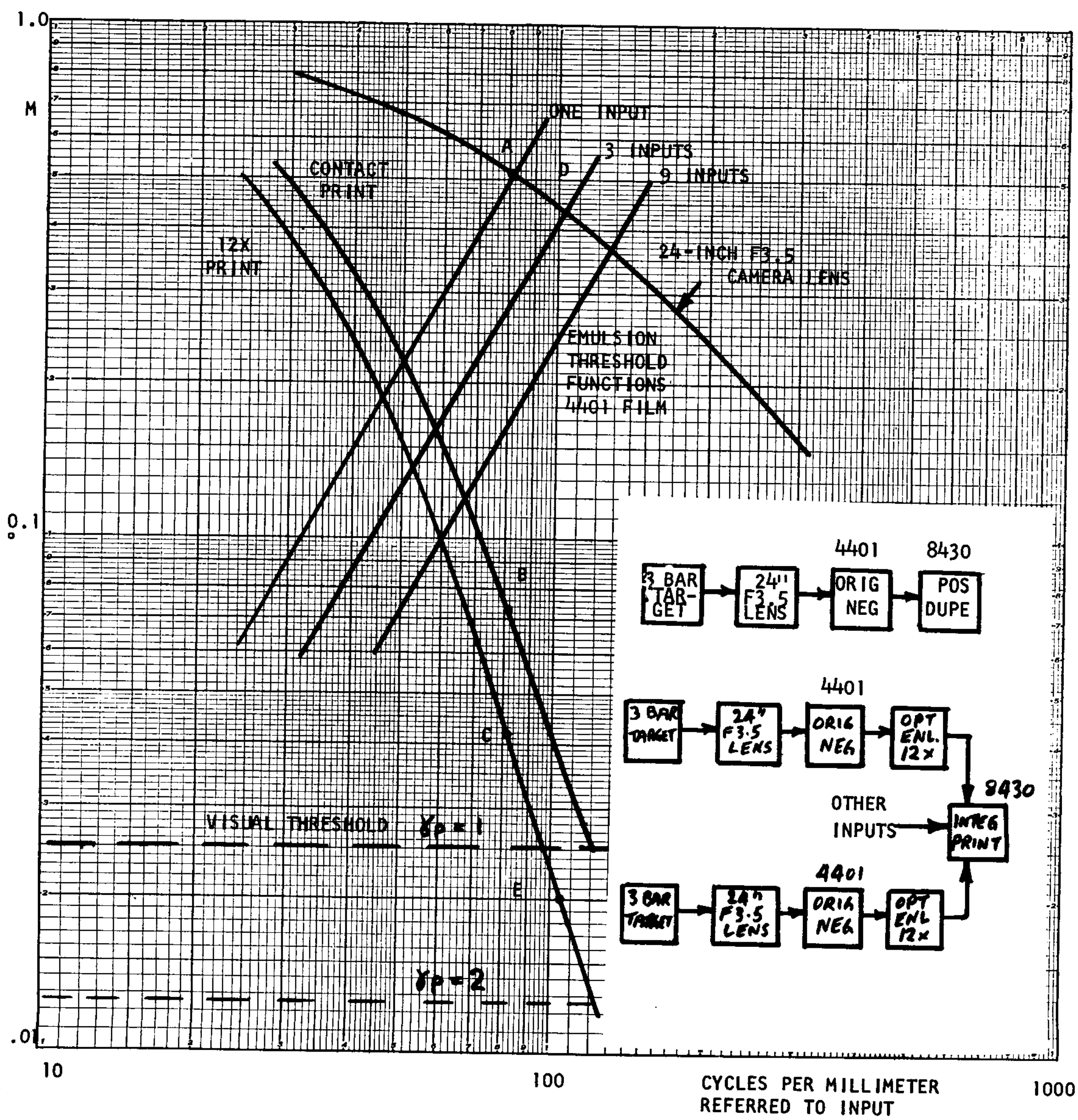


FIGURE 7
OPTICAL IMAGE INTEGRATION. FILM LIMITED SYSTEM - ORIGINAL NEGATIVE ON 4401 FILM

This is a "film limited system" in that the lens is capable of a much higher resolution than the film can record. Using a high contrast bar target and assuming no other degradation, the incident modulation on the film will follow the same curve as the lens MTF, as shown. A contact print on 8430 duplicating stock will have the MTF shown, again assuming no further degradation in the contact printer. A 12x print obtained from the O/N with a high quality optical enlarger will have the MTF shown.

If there were no granularity on the film, then the resolving power of the system, referred to the negative, would be about 120 cycles/mm on the contact print and 100 cycles/mm on the 12x enlargement for a print gamma of 1. However, the emulsion threshold function crosses the incident modulation curve at point A, showing that film granularity has decreased the resolving power to about 82 cycles/mm. The actual modulation obtained on the contact print and 12x enlargement at this resolution is shown at points B and C. (Note: Due to the granularity of the 8430 dupe stock, the threshold for the contact print would in fact be higher than shown, resulting in a lower resolving power on the contact print than on the enlargement. The granularity contributed by the 8430 film to the 12x print would be negligible). When 3 inputs and 9 inputs are integrated, the emulsion threshold curves are reduced by factors of 1.73 and 3 respectively. The 3-input threshold crosses the incident modulation curve at point D, at a resolution of just over 100 cycles/mm. This improvement would only be seen if the gamma of the enlarged print were greater than about 1.5, otherwise the point F would be below the visual threshold. Integration of more than

3 inputs would be of doubtful value as the contrast improvement would be below the visual threshold unless very high printing gammas were used. However, signal-to-noise ratio at spatial frequencies in the range 15-100 cycles per millimeter is improved by a factor of roughly $\sqrt{N}$.

Figure 8 shows the performance of a similar system except for the use of 3404 high resolution film for the original negative. This film has a higher MTF than the lens, so the system is therefore "non-film limited". The visual resolving power of this system for contact prints or enlargements is shown at points D and C for gamma = 1 and is limited by the visual threshold, not by the granularity. Even with a very high printing gamma, it would be difficult to see detail at 230 cycles/mm which is the threshold due to granularity. Because of this, the use of image integration does not confer any improvement in resolution in this system. There is still, however, an improvement of $\sqrt{N}$ in signal to noise ratio at spatial frequencies between about 50 and 150 cycles/mm. What can be done to improve resolution? The major limiting factor has been the use of a conventional enlarger designed to cover relatively large image areas, at a sacrifice in resolution. If we are prepared to confine image integration to very small areas of the order of 1mm square, then much higher resolution can be obtained by the use of microscope objectives. A suitable objective is the Beck Model 25-050 reflecting objective of 13mm focal length. This has an aperture of better than f/2 and is diffraction limited. The MTF of this lens is shown in Figure 9, and the resulting MTF of a 90x enlargement onto a 3 x 3 inch print is shown. It can be seen that an improvement from about 230 to 310 cycles/mm is obtained through the integration of 3 inputs, but that further improvement would be difficult to obtain. The practical problems of building a piece of equipment to do this job are very considerable.

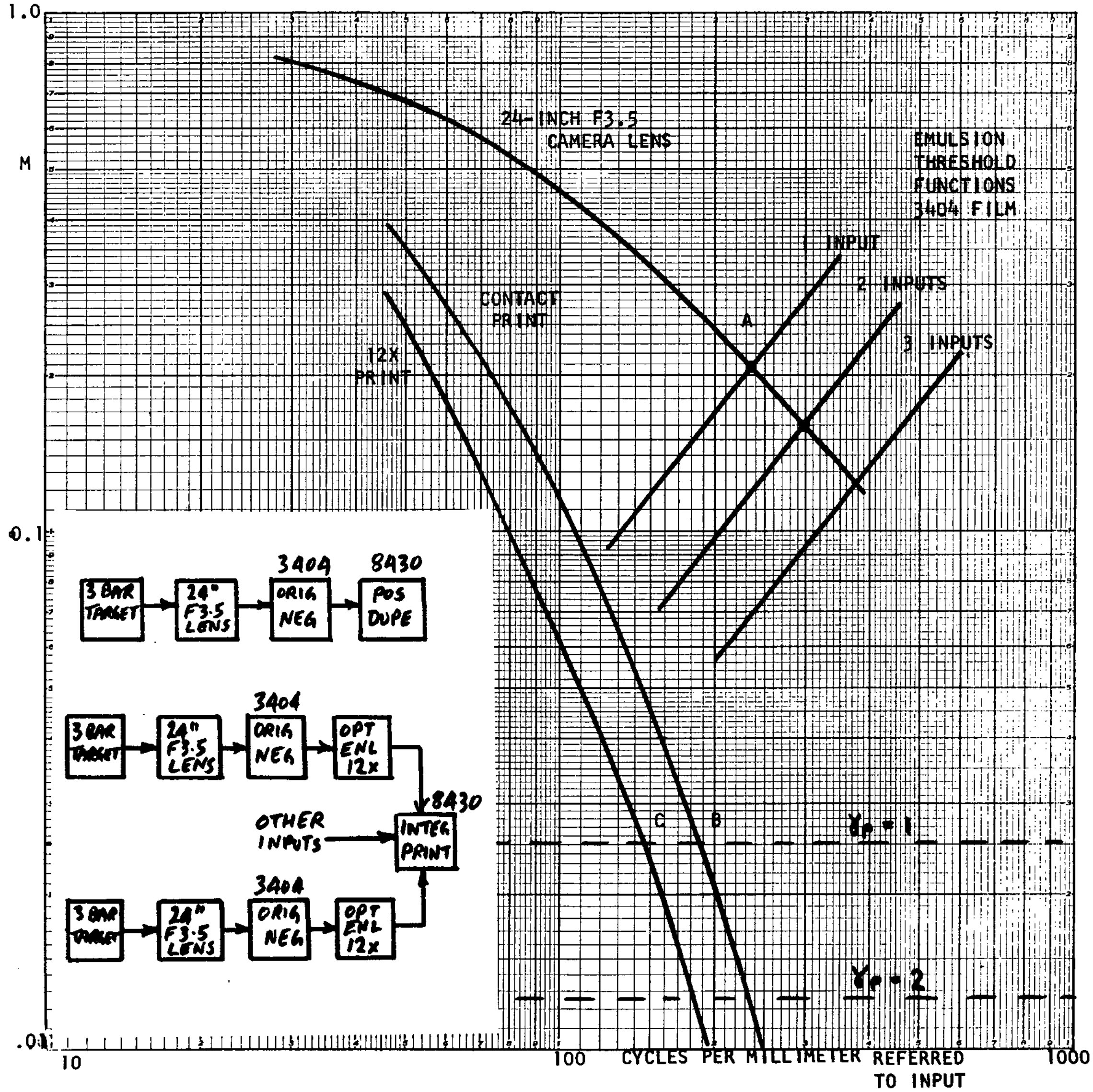


FIGURE 8

OPTICAL IMAGE INTEGRATION
NON-FILM LIMITED SYSTEM

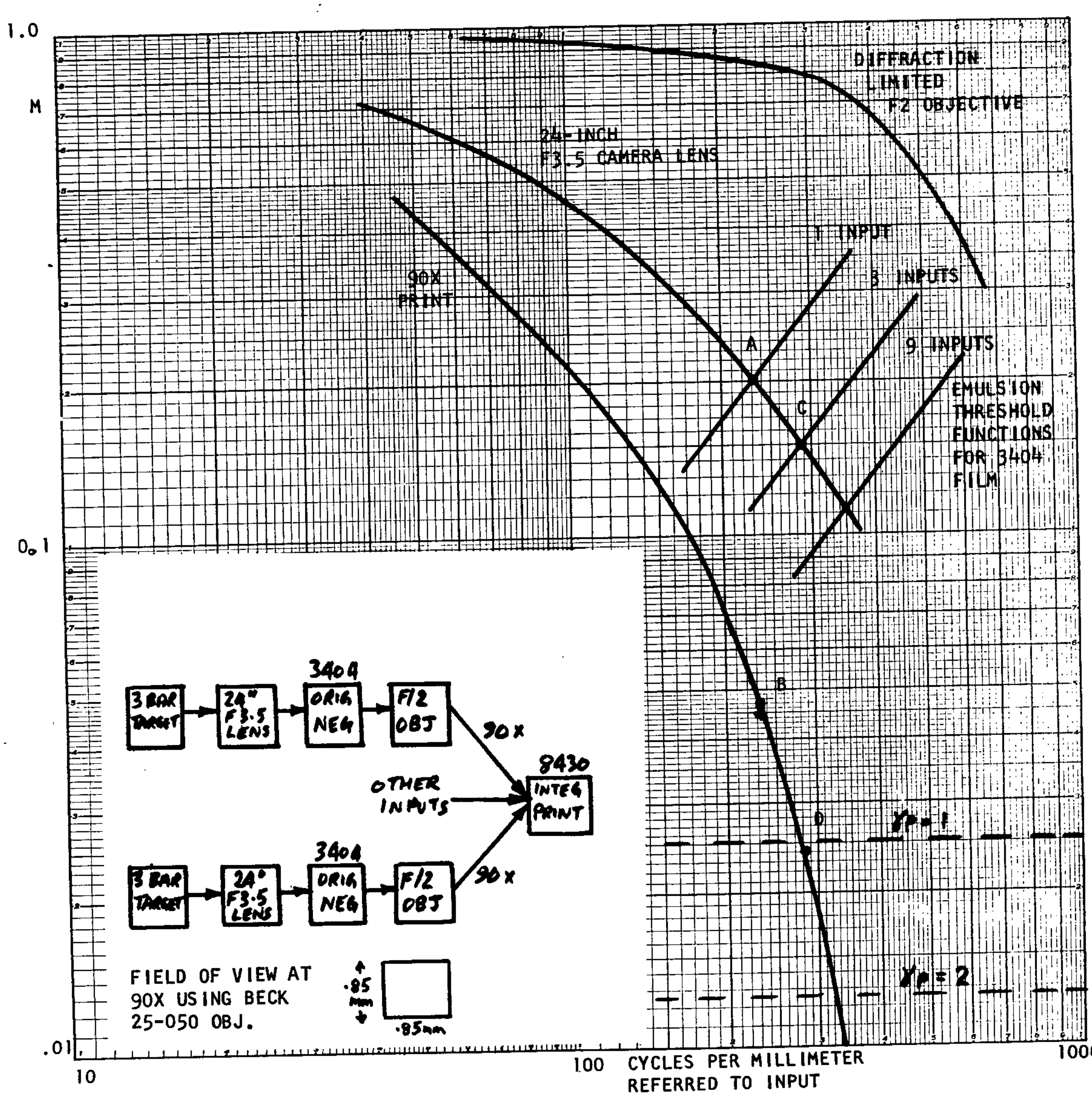


FIGURE 9

OPTICAL IMAGE INTEGRATION

5.0 ELECTRONIC IMAGE INTEGRATION

Because of its ability to correct first and higher order image distortions and its capability for image processing, an electronic imaging system is an attractive proposition for image integration. A direct viewing system of the required resolution is not feasible because of the limited bandwidth of the video chain. The bandwidth required to scan, process and display a 3000 line picture at a 30 c/s frame rate is beyond the present state-of-the-art.

The most effective way to use an electronic system is to employ a slow-scan readout onto film. In this way, bandwidth limitations are overcome and a high resolution hard copy is obtained.

Figure 10 shows the modulation transfer functions of a high resolution cathode ray tube and an image dissector tube. Resolution is normalized to line pairs per frame height so a direct comparison can be made. While the CRT with a 1 mil spot has a higher resolving power, it can be seen that in the region below the crossover the image dissector has considerably better response. This is due to the fact that it uses an aperture with a rectangular response rather than a gaussian shaped spot. The image dissector is therefore superior to CRT flying spot scanner as an image pick-up device. The CRT is used for printing out the integrated image onto film.

The performance of an electronic image integration printer is shown in Figure 11. The block diagram shows the various stages whose MTF's has to be cascaded in order to determine overall performance of the system. By using a slow-scan system, in which the image is laid down on the output print line by line over a period of a few seconds, the bandwidth required

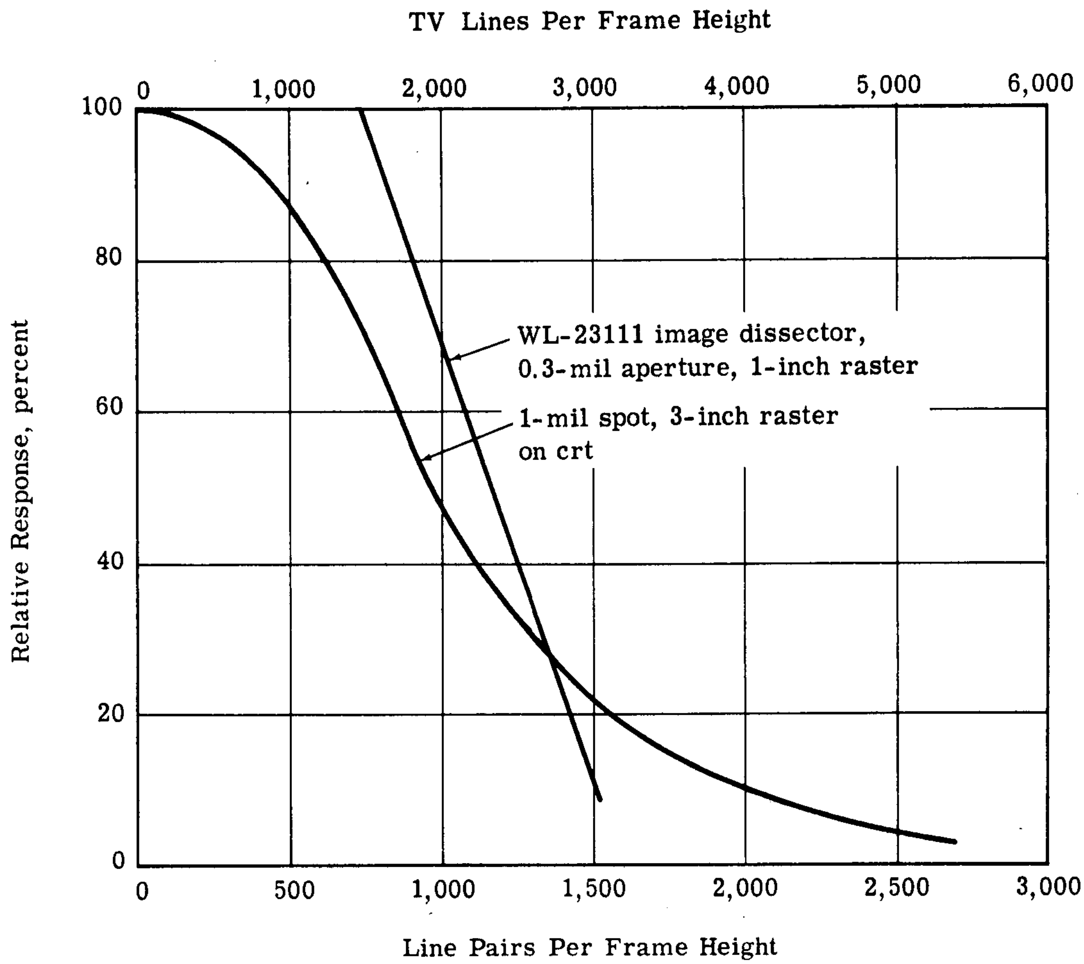


Figure 10 — Modulation transfer functions for cathode-ray tube and image dissector, linear plot

in the video summing and processing circuit is reduced and is no longer a limiting factor. At large magnifications, the MTF's of the CRT imaging lens and output film can also be ignored.

The modulation transfer function of a 90x print, referred to the input film, is shown in Figure 11 as are the emulsion thresholds for 3404 film for 1, 3 and 9 inputs. The resolution obtained with a single input is shown at B and is 230 cycles/mm. With 3 inputs, the resolution potentially increases to 280 cycles/mm and with 9 inputs the resolution is potentially 340 cycles/mm. Whether or not this improvement is actually obtained depends on the signal-to-noise ratio of the electronic system. There is no fixed visual threshold in an electronic system because the contrast can be expanded electrically to any required degree. The only limitation is in the signal-to-noise ratio in expanding the contrast, small signal fluctuations due to noise are also expanded. The real limitation to resolution in an electronic viewer may therefore be noise. Little information on the subjective effect of visual noise on the recognition of objects is available. It has been found experimentally that it is difficult to detect an image when the RMS signal-to-noise ratio is less than about 7:1. Thus, to detect an image modulation of 7 percent, the RMS noise would have to be 1 percent of peak modulation, or 40db down. To detect a modulation of 2-1/2 percent, the normal visual threshold, a signal-to-noise ratio of 50db would be required.

The block diagram of an electronic image integration system is shown in Figure 12. This system employs automatic image registration for alignment of the 3 inputs, with a low resolution visual monitor.

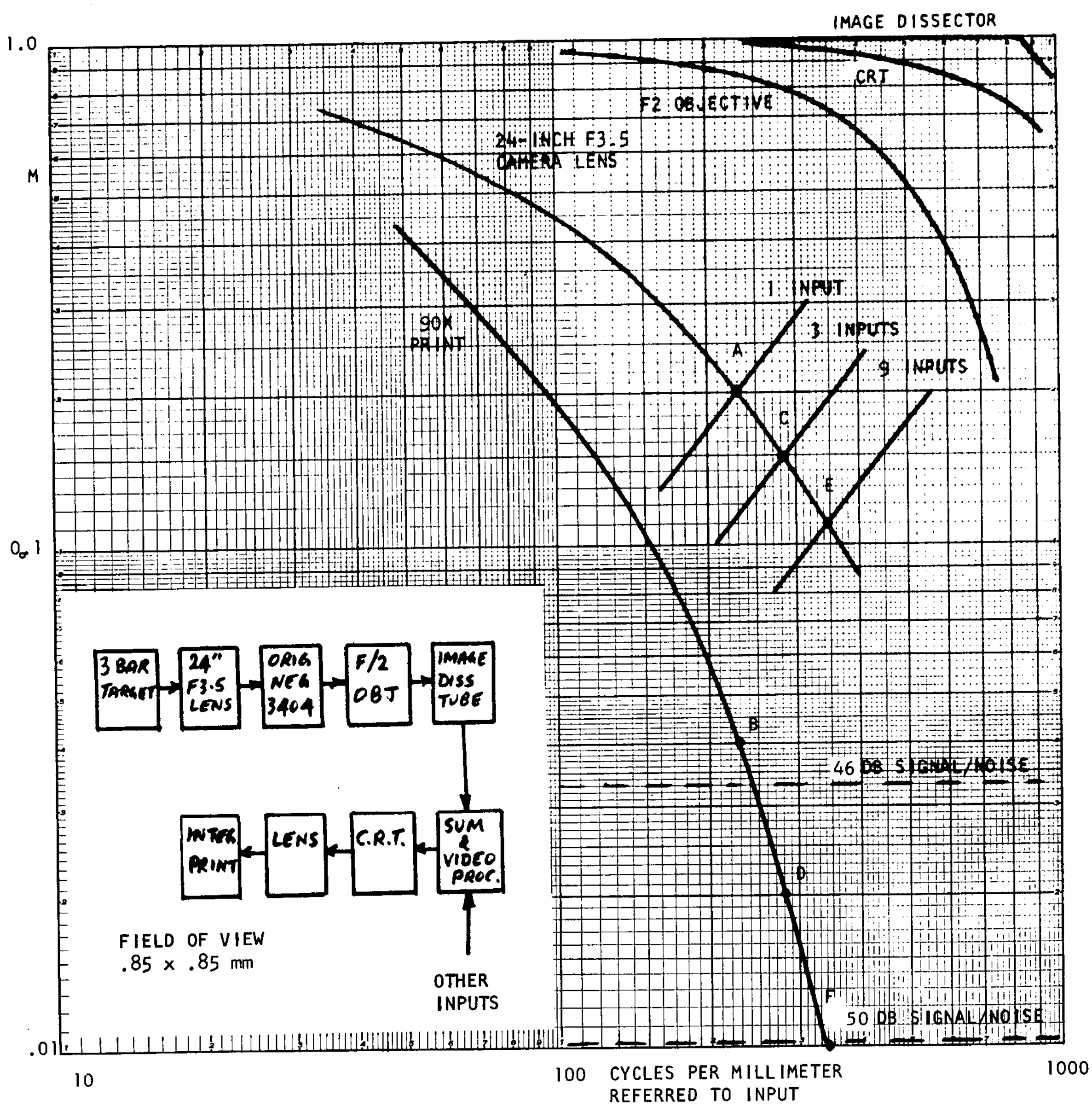


FIGURE 11

ELECTRONIC IMAGE INTEGRATION
USING HIGH MAGNIFICATION

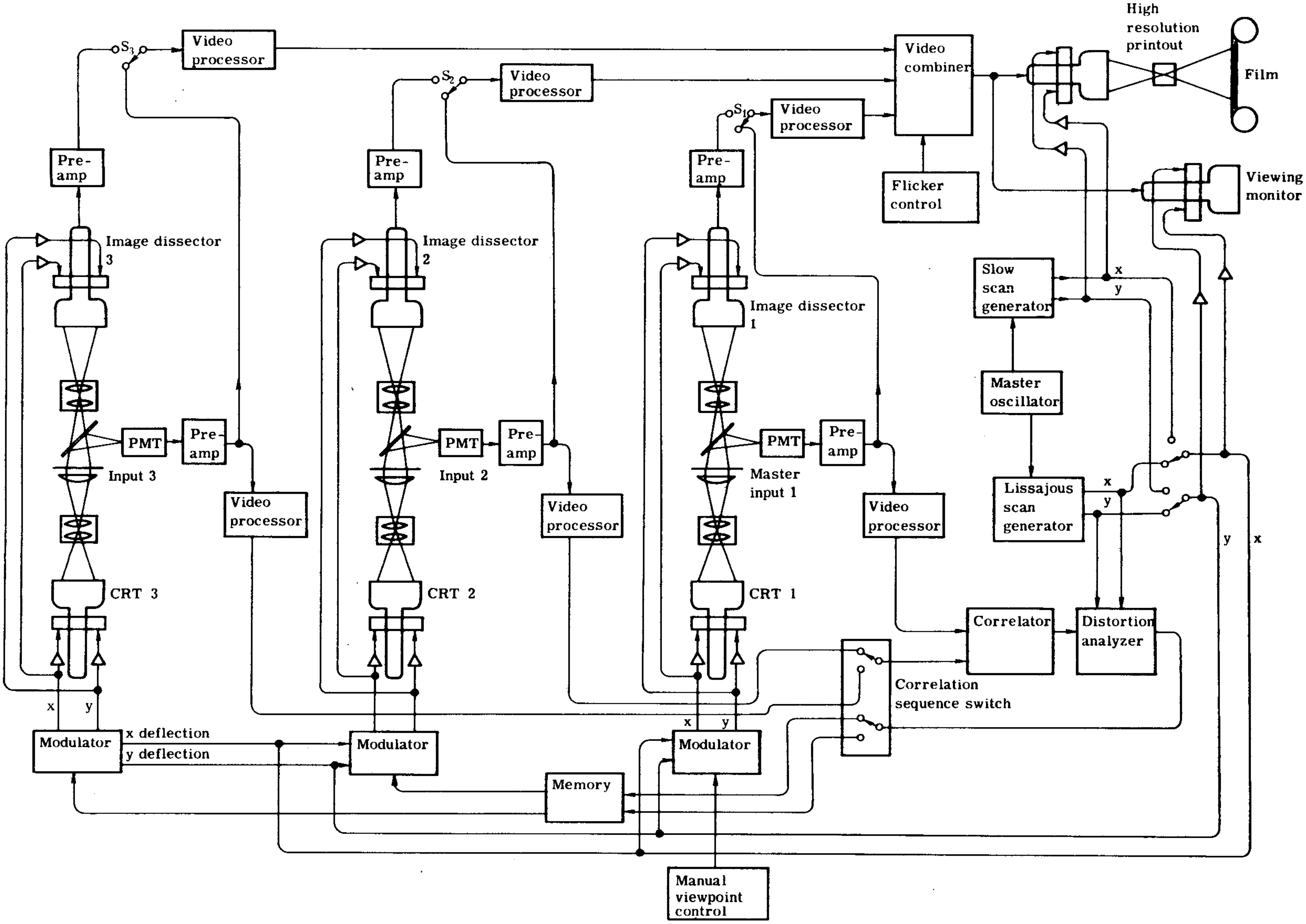


Figure 12— Block diagram of multiple image integration viewer-printer

5.1 Automatic Registration

The performance of an automatic registration image integration printer depends greatly on the accuracy that can be achieved with image registration. It was previously shown that displacements of only a few microns can degrade any improvement in resolution due to integration.

Current experience at [redacted] indicates that the positioning accuracy achievable with automatic registration at the present state-of-the-art is given by $\triangle = a/1000$ where a is the side of the scanned area on film.

For a scanned area of 0.85 millimeter square, the alignment accuracy is then .85 microns. Referring back to the section on image alignment, we find that this displacement will limit resolution to about 300 cycles/mm. With a large number of inputs, each having a similar displacement, the resolution will be limited still further. If we assume that the misalignments add on an RMS basis, we find that for 3 inputs (2 matching operations) the resolution is limited to about 210 cycles/mm while for 9 inputs the resolution due to misalignment would drop to 110 cycles/mm.

Another problem with automatic image registration is the presence of relief distortion. Figure 14 shows a small object viewed from two aspect angles. It is required to examine the top of this object in detail. If the two photographs of this object are scanned and the average parallax eliminated, then the top of the object will be displaced. The distortion represented by this displacement is of a very high order, and no existing correlator will sense and correct it. The top of the object can be aligned manually by displacing the whole frame. A better solution is to increase magnification until the area of interest fills the entire frame.

When this is done, clearance of the average parallax, together with correction of first order distortion if the image or camera is tilted, will provide good alignment. This provides another reason for preferring the integration of small image areas, in addition to the desirability of increasing system resolution.

6.0 EVALUATION OF RESULTS

Because many of the factors involved in image integration are subjective, such as the effect of granularity in recognition of a specific shape or form, a definitive evaluation of the potentialities of image integration can only be found by experiment. This entails building an image integration system capable of handling high resolution material, and conducting an extensive series of tests. This was the approach suggested at the conclusion of Phase I and a suitable design, described in detail in the feasibility report, was proposed. However, such an approach would be very costly and there is no guarantee that an operationally useful piece of equipment would result.

The performance predictions in this summary report are the best that can be made with information presently available. In making these predictions, various assumptions were necessary and will be summarized before the conclusions of the study are discussed.

(1) The emulsion threshold functions were measured using 3-bar targets. Emulsion threshold functions for real aerial imagery are not available and may be different.

(2) The magnitude of the emulsion threshold function was assumed to be proportional to the RMS granularity of the film.

(3) Effects of image motion, haze and atmospheric turbulence have not been included.

(4) The effects of small misalignments on the detectability of real detail in aerial imagery are not known. Predictions are based on sine-wave images.

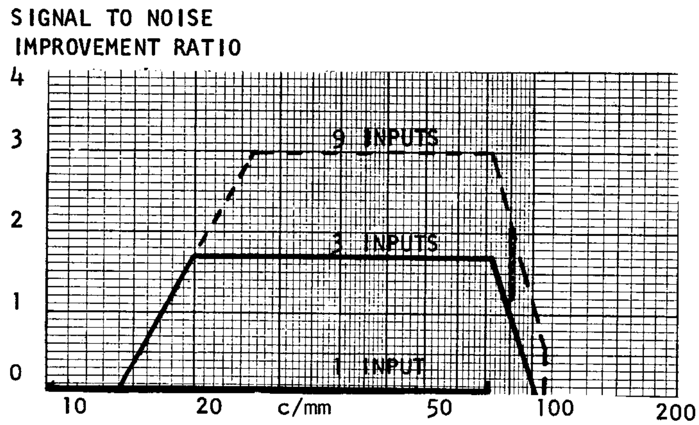
(5) Miscellaneous effects such as vibration, dust, lack of sharp focus have been ignored. The results presented are therefore likely to be somewhat optimistic.

The results of the image integration study are summarized in Figure 13, which shows the improvement in signal-to-noise ratio and resolution for each of the four systems analyzed. The red lines represent the probable limits of resolution due to a misalignment of 1 micron at each film. With this misalignment, the resolution with 3 inputs would be reduced to about 180 cycles/mm and with 9 inputs would be reduced to about 90 cycles/mm. Resolution limits for the electronic system are based on the expected accuracy of the automatic registration equipment.

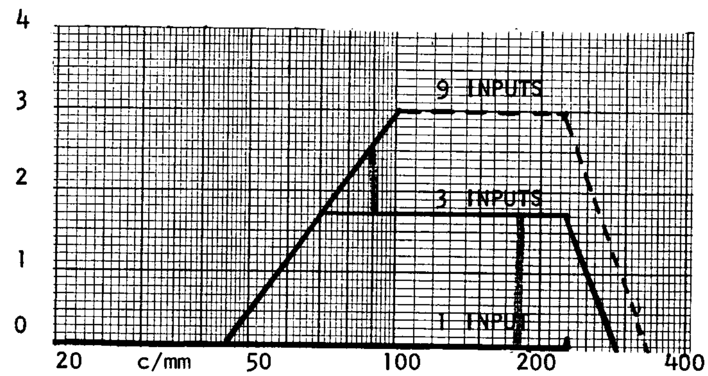
It can be seen that while an increase is obtained in signal to noise ratio at high spatial frequencies in all cases, the actual increase in resolution is either very modest or nonexistent. In fact, with the alignment accuracies likely to be encountered in practice, the resolution of the integrated image may be worse than one of the inputs.

The benefit of the increased signal to noise ratio should not be underestimated, as a great deal of useful detail exists within the range 20 - 100 cycles/mm and visibility of this detail would be improved.

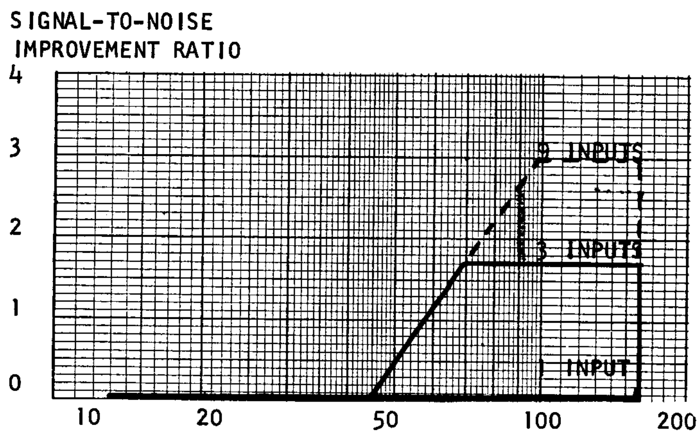
On balance, it does not appear that the value of image integration equipment, using direct addition of images, would be worth the probable cost, for the photointerpreting operation. It is recommended that a broader approach to image processing be made, using more sophisticated techniques.



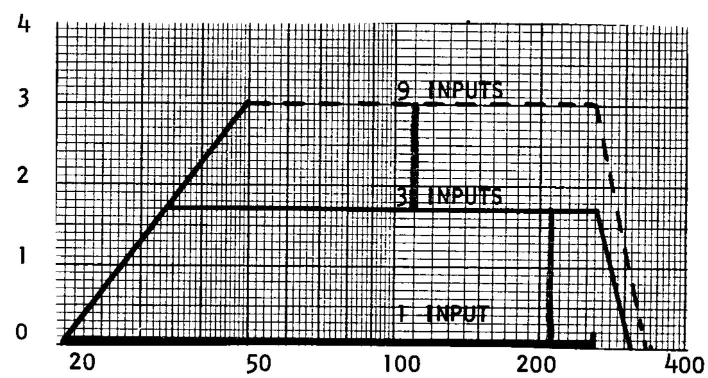
OPTICAL IMAGE INTEGRATION
FILM LIMITED SYSTEM



OPTICAL IMAGE INTEGRATION
HIGH MAGNIFICATION



OPTICAL IMAGE INTEGRATION
NON-FILM LIMITED SYSTEM



ELECTRONIC IMAGE INTEGRATION
HIGH MAGNIFICATION

FIGURE 13

SUMMARY OF IMAGE INTEGRATION SYSTEM PERFORMANCE

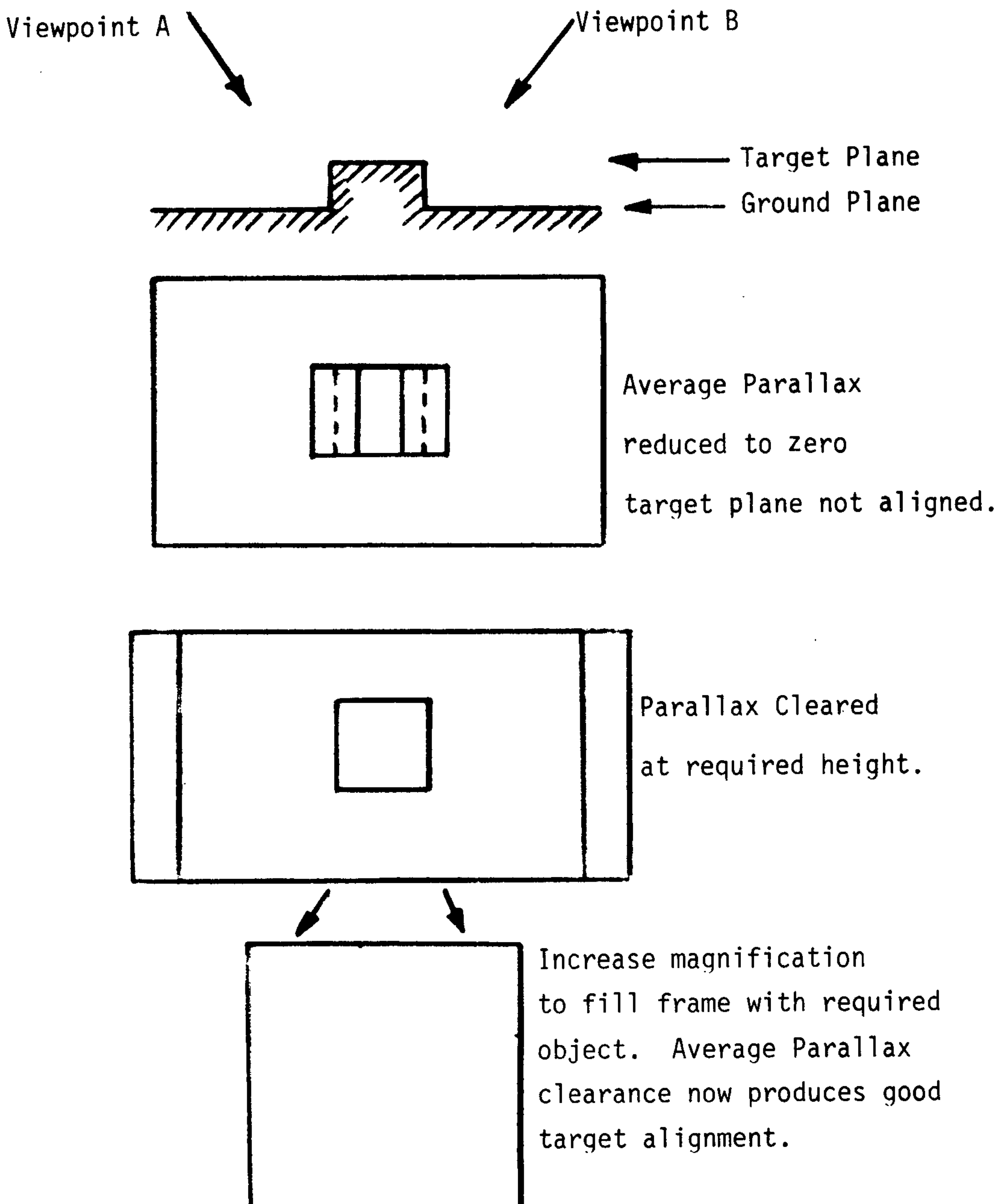


Figure 14. Relief Displacements.

SECTION II

IMAGE INTEGRATION

PROGRAM RECOMMENDATIONS

19 January 1967

Section 1.0

INTRODUCTION

1.0 INTRODUCTION

Inasmuch as the conclusions drawn from the work to date indicate that the construction of a piece of equipment as originally contemplated will not produce image improvements compatible with the effort of fabrication or operation; we strongly recommend that the scope of the contract be changed.

The original aim of the task was to provide a relatively simple method of obtaining images of improved quality from multiple samples. Our work has shown that the simple approach is inadequate. If improved images are desired then the technique utilized must be more sophisticated and more immediate results might be obtained by aiming at a less ambitious goal, insofar as the size of the image is concerned. In the past few years considerable advances have been made by applying some of the developments of information theory and communication theory to the treatment of optical images. The recent work done on the improvement of the Surveyor pictures and the work being done under [redacted] STAT are examples of this.

It is our recommendation that the program be continued toward the solution of the image integration problem using a combination of the ARES type registration and distortion technique and the digital processing technique. If it is felt that this is inappropriate then we suggest that the remaining funds be directed toward similar aspects of the Stereo Scanning research program. Both of these alternatives are described in more detail in the following material.

Section 2.0

TECHNICAL DISCUSSION

2.0 TECHNICAL DISCUSSION

In any system used for the transmission of information, it is noise that limits the amount of information transmitted. Noise in this sense is defined as any undesired component in the received information. In the case of photographic images, there are a large number of noise sources as well as different types of noise. A single image can be limited by image smear, high fog level, grain noise, poor focus, atmospheric turbulence, lens aberrations or other sources. In some cases, such as image smear due to faulty IMC, or due to known lens aberrations, the effect of the "noise" can be predicted with considerable accuracy. In principle, it is possible in these cases to correct the transmission to compensate for the degradation produced by the noise. The most common example of this is, of course, the eyeglasses many people wear, and perhaps the least common is the digital processing that has been done to correct for faulty IMC. In between are the aperture correction networks used in TV systems. In radio and telephony this practice of linear equalization has been used for many years and the theory is quite well developed.

This process of equalization applies to a time invarient "noise" and, of course, applies to either single or multiple transmissions or images.

The problem of correction with systems in which the noise varies (i.e. atmospheric turbulence in images, or multipath interference in radio) must be handled differently. In some cases, a known reference signal is transmitted as part of the total signal and is used as a basis for determining the nature of the noise. It has recently been suggested that known, or suspected, point objects in noisy images might serve this function. In the case of radio transmission through slowly changing multipath interference, it is possible by using active filter systems in a feedback control network to automatically track the interference. Conceptually, this might also be done in the correction of movies taken through turbulence, depending, of course, on the frame rates and rate of change of the wavefront deformations.

Extrapolation of the noise treatment principles used in the one dimensional world of electrical signals to those of the two dimensional world of optical images, is not as simple as it might first appear. The relatively simple technique of spatial frequency filtering using coherent light offers a means of passing selected frequencies, but it is not easily adapted to smoothly varying attenuation with spatial frequency, and it is even more difficult to obtain varying phase modulation.

An optical system is unsurpassed in its information handling capacity, but once such a system is set up it is relatively fixed insofar as being able to alter its complex modulation transfer function. For this reason, most of the work on the study of image noise and its treatment is being done on electrical signals obtained by scanning the image with an electro-optical device.

For the type of study and treatment in which we are most interested, i.e. multiple image integration, the most promising technique is to break down the image or images into their separate resolution elements and store this data in a digital computer. In this situation the images can be operated upon in a pure mathematical sense in a noise free environment. As is usual, the penalty to be paid for this ideal treatment is time, or total information capacity. There is always the hope, however, that once a processing technique has been proven to be successful, that an optical system to accomplish the same ends can be designed. Certainly, no assurances of the practicality of this can be given as yet.

An example of early work in the field of image improvement is shown in the first illustration. This is Fig. 6 from a paper by Kovasznay and Joseph, entitled "Image Processing", which appeared in the Proceedings of the IRE, Volume 43, Number 5, May 1955. In this case a crossed diagonal Lissajous scan was used in order to obtain a one dimensional electrical signal which contained contributions from both image dimensions. The figure shown here is a third generation halftone and most of

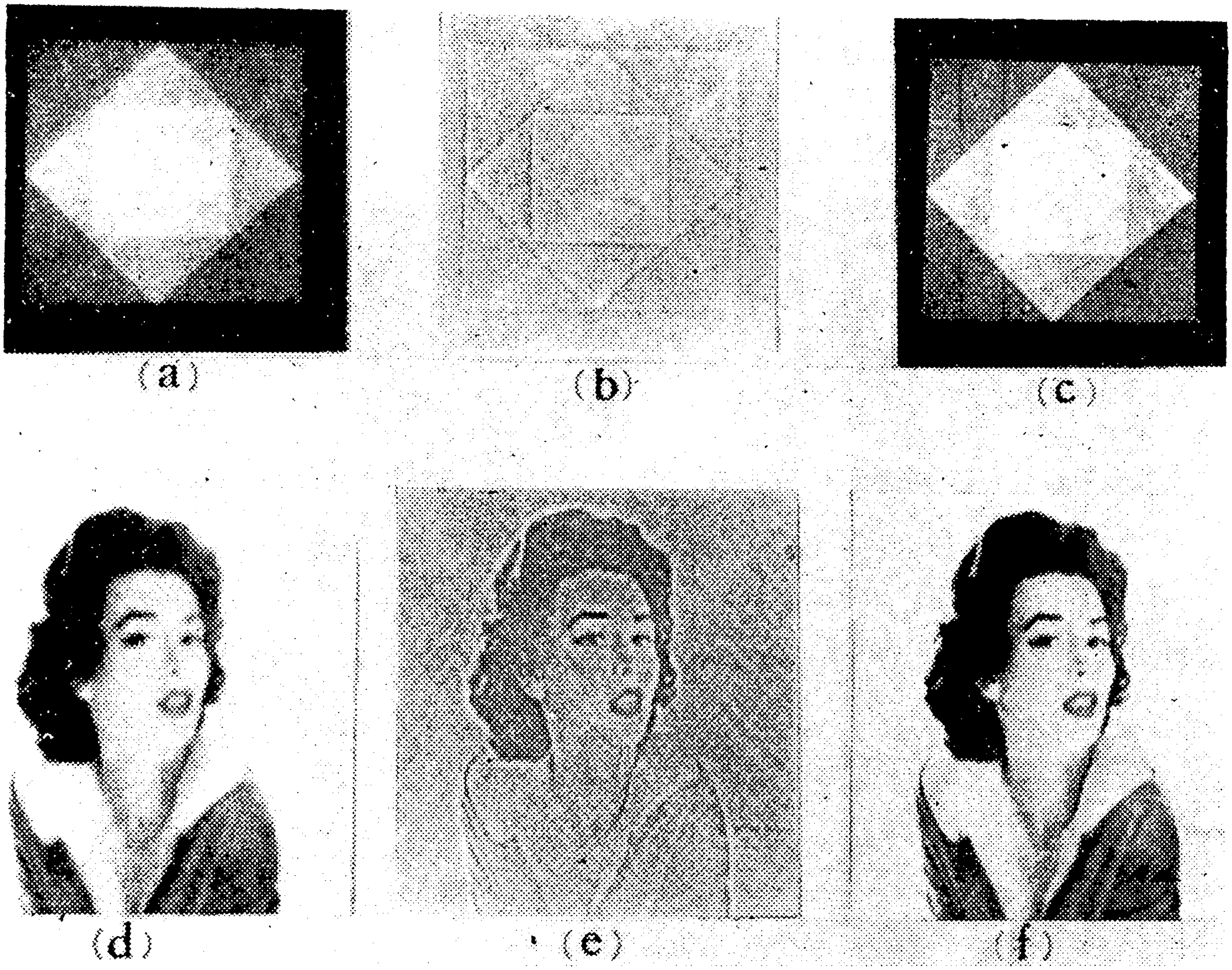


Fig. 6—Experiments in contour enhancement. (a) Blurred original picture, (b) correcting signal (negative Laplacian), (c) enhanced resulting picture, (d) blurred original picture, (e) correcting signal (negative Laplacian), (f) enhanced resulting picture.

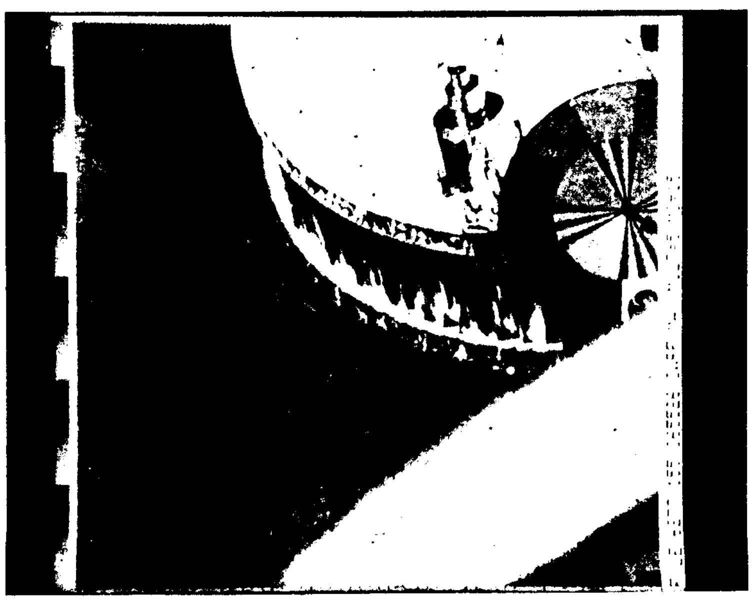
the improved detail has been lost.

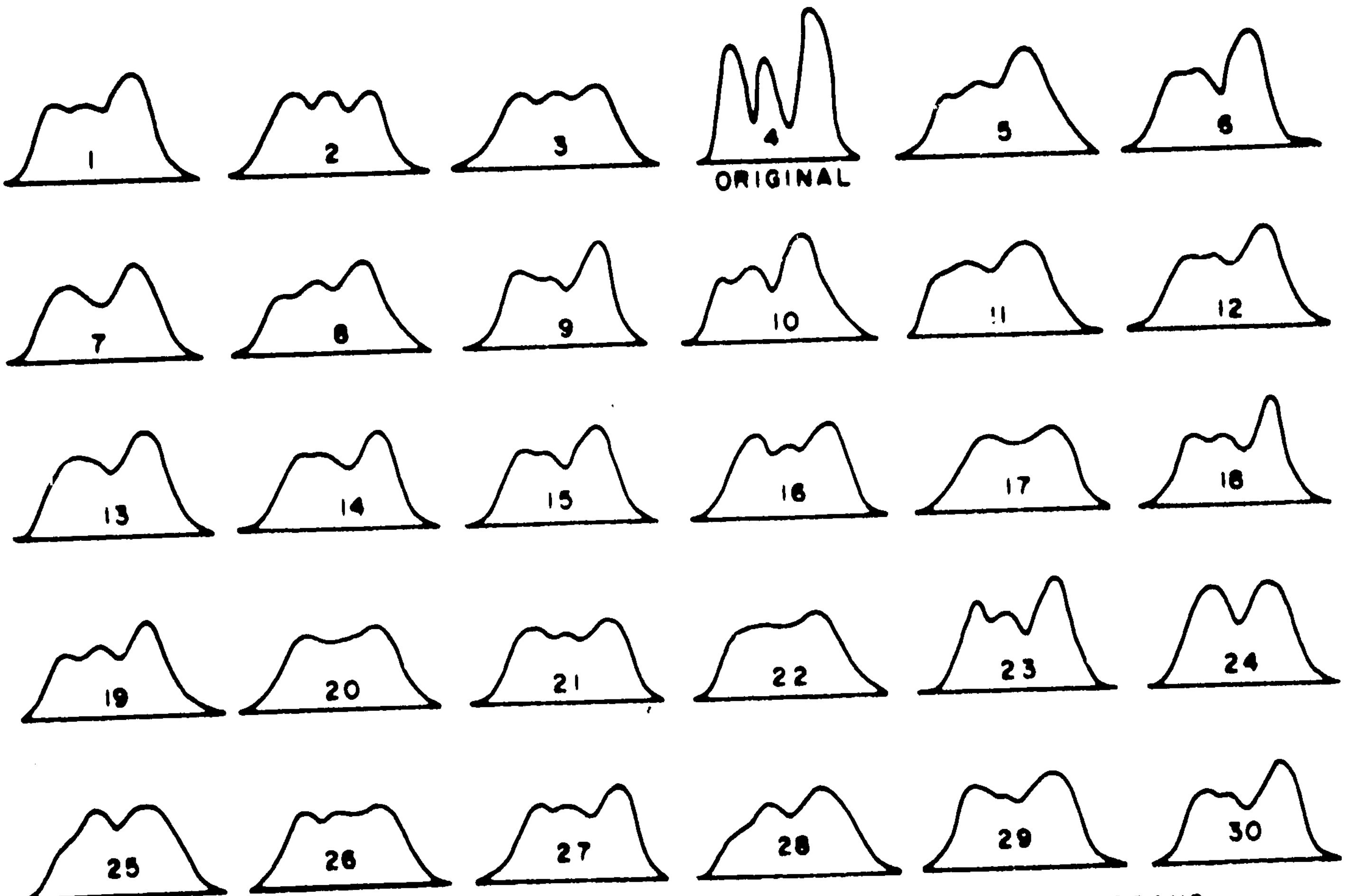
Jumping ahead a few years, the second illustration is a reproduction of Figs. 11 and 12 from the article "The Surveyor Lunar Landing Television System" by Montgomery and Wolf that appeared in the IEEE Spectrum of August 1966. In this instance the image processing was done by a digital computer programmed to equalize the camera performance based on data obtained from a series of calibration tests performed on the camera prior to launch.

Insofar as the post detection processing of multiple images is concerned, [redacted] appears to have been doing the most promising work. In 1962 he conducted an experiment in which he scanned a single line of the image of a three filament lamp in the presence of atmospheric turbulence created by a hot-plate. As a result of 29 such line scans he obtained 29 different line scan waveforms. By operating upon the Fourier transforms of these waveforms, he was able to reconstruct an improved waveform which looked very much like the result of scanning the image in the absence of the turbulence. The specific waveforms are shown in the following illustrations which are Figs. 18 and 22 from his progress report of March 1963 entitled "Restoration of Atmospherically Distorted Images", Bureau of Ships, Contract Nobs-84075.

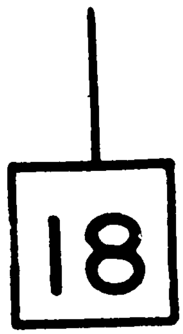
Fig. 11. Surveyor I unprocessed photograph of the lunar surface showing the spacecraft footpad, photometric chart, and the lunar surface disturbed by the spacecraft during landing.

Fig. 12. Same photograph as in Fig. 11 with sine-wave correction applied.





TRACING OF UNDISTORTED SCOPE SCAN AND 29 DISTORTED SCANS



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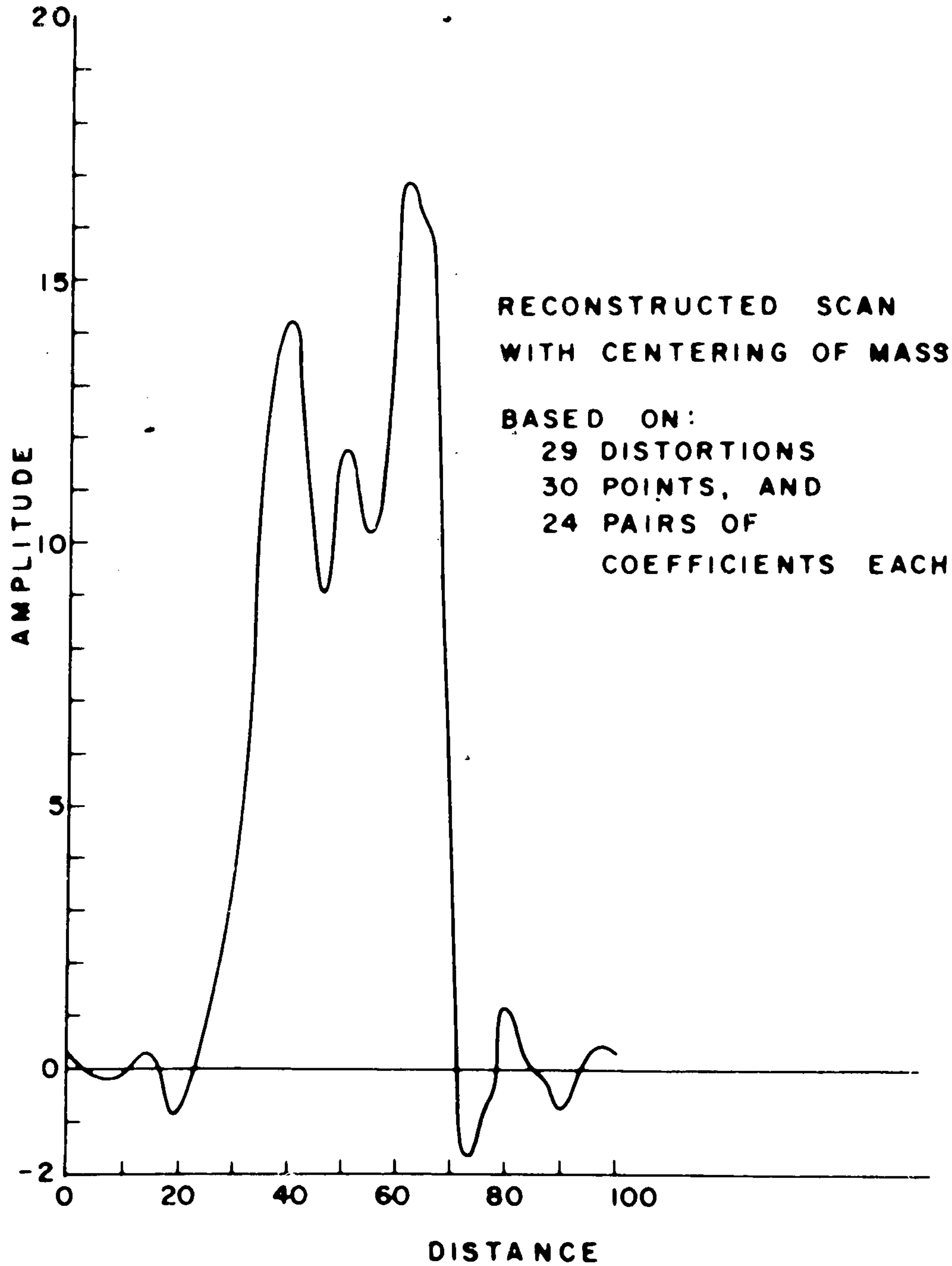

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The specific technique used in the image restoration was to examine the complex Fourier transforms of each of the scans and to construct a new transform in which the amplitude assigned a specific spatial frequency component was the peak amplitude found at that frequency in the group of samples. This new transform was then retransformed to obtain the reconstruction.

Although the numerical analysis of the waveforms was carried out with only 30 points on each waveform, which effectively means very low resolution, it was found necessary to center the waveforms prior to the transformations in order to obtain good results.

This centering problem is a registration problem very similar to that found to be very serious in the tests [redacted] This is also the type STAT of effect that the ARES distortion removal technique is ideally suited to remove, particularly if the number of resolution elements across the image is limited to of the order of 100 or less.

It would appear obvious that the next step in the work of [redacted]. STAT would be to apply his technique of processing to two dimensional images. As a consequence of this it is somewhat peculiar that the results of such processing attempts have not been reported to our knowledge, although the previously mentioned progress report outlined detailed plans to conduct such experiments. Any new work in this area should certainly include a determination of the results of [redacted] work on two dimensional images. STAT

A relatively recent development in the computation of two dimensional Fourier transforms, the Cooley-Tukey technique, has made possible an immense reduction in the time required in the computation of such transforms. The transformation of 64 x 64 arrays of points is now a routine operation in the analysis of lens performance data.

In the summer of 1966, a summer study on image restoration sponsored by the National Science Foundation was held at Woods Hole, Massachusetts. One of the conclusions of this study was that the most promising image processing technique was the use of high speed digital computers and the Cooley-Tukey transformation program.

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Section 3.0

PROPOSED PROGRAM

3.0 PROPOSED PROGRAM

As the next phase of this program, we propose to demonstrate the feasibility of the integration of multiple images using a digital computer and a computer controlled scanner/display system. All of the equipment required, is on hand and available. Most of the computer programs are also available. The bulk of the work to be done will be devising the remaining programs and developing the mathematical support and analysis.

The aim of the work is to develop and implement the following sequence of operations:

1. Select a number of image samples, 10-30.
2. Using a 64 x 64 raster, scan and store first image.
3. Scan first image with a distortion detection scan and store.
4. Scan second image with an ARES type scan and compare with first.
5. Correct the scan to reduce distortions to zero.
6. Using a distorted 64 x 64 raster scan and store second image.
7. Repeat steps 4 through 6 on remaining images.
8. Prepare punch cards on all stored images.
9. Use CDC-3300 to obtain complex 2D transforms of all images.

10. Synthesize the ideal complex 2D transform.

11. Retransform.

12. Display.

The equipment to be used consists of a PDP-1 computer with scanner and display unit, to be used for image scanning and correction of zero and first order distortions; and the CDC-3300 computer system to be used for the Fourier transformations and synthesis of the improved transform.

The computer programs that have already been written and are available are:

PDP-1:

Crossed Diagonal Scan

Distortion Detection

64 x 64 Scanning

Display

CDC-3300:

Fourier Transforms

In addition to these special programs, both systems have extensive program libraries.

The programs to be written to complete the suggested sequence are:

1. Automatic distortion correction. This program to use the detected distortions to predistort the crossed diagonal

scan so that by successive scans the distortion errors can be reduced to zero. The scan distortion then to be applied to the 64 x 64 scan when the image is scanned and stored.

2. Synthesis of the complex 2D transform from the transforms of the sample images. This program will be a two dimensional version of [redacted] peak selection process. STAT

It is almost certain that this program is not as simple as it sounds. The first tests will be done with artificial images to test that the actual process is working as expected. If the first tests are successful, then simple examples of real images will be used. Finally, real images taken from different points of view will be examined.

Image processing can be stated as the problem of solving an integral equation of the form

$$b(y) = \int g(y, x)\, a(x)\,dx$$

$a(x)$ = object distribution

$g(y, x)$ = imaging kernel (point response)

$b(y)$ = image distribution

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An equation of this type holds whether the light forming the image is totally coherent, totally incoherent, or partially coherent, although the imaging kernel and the object functions represent complex disturbances in one case and intensity in another.

The fundamental problem is to solve for the object function given the image function and the kernel. However, the exact form of the kernel must be determined prior to attempting any solution. Any error in determination of either the image distribution b(y) or in the point response g(y, x), will lead to corresponding errors in the reconstructed object function.

The task of determining the forms the kernel might take in the presence of degrading influences during the imaging process and of devising appropriate exact or approximate solutions whether the kernel be given in statistical or deterministic terms, will be the prime concern of the mathematical analyst. This task will hopefully lead to the formulation in terms suitable for the computer of algorithms embodying the solution concepts.

Secondarily, the analyst will be concerned with the supervision of the activities of the programmer, to ensure the proper implementation of the various algorithms for machine solution of the image integration problems.

We propose that the status of the work be continually communicated to the sponsor and that the work be halted and reviewed if at any time a serious stumbling block or fundamental deficiency is encountered. On the other hand, if these tests prove to be successful then we shall propose to increase the information capacity or resolution of the images.

Section 4.0

SCHEDULE

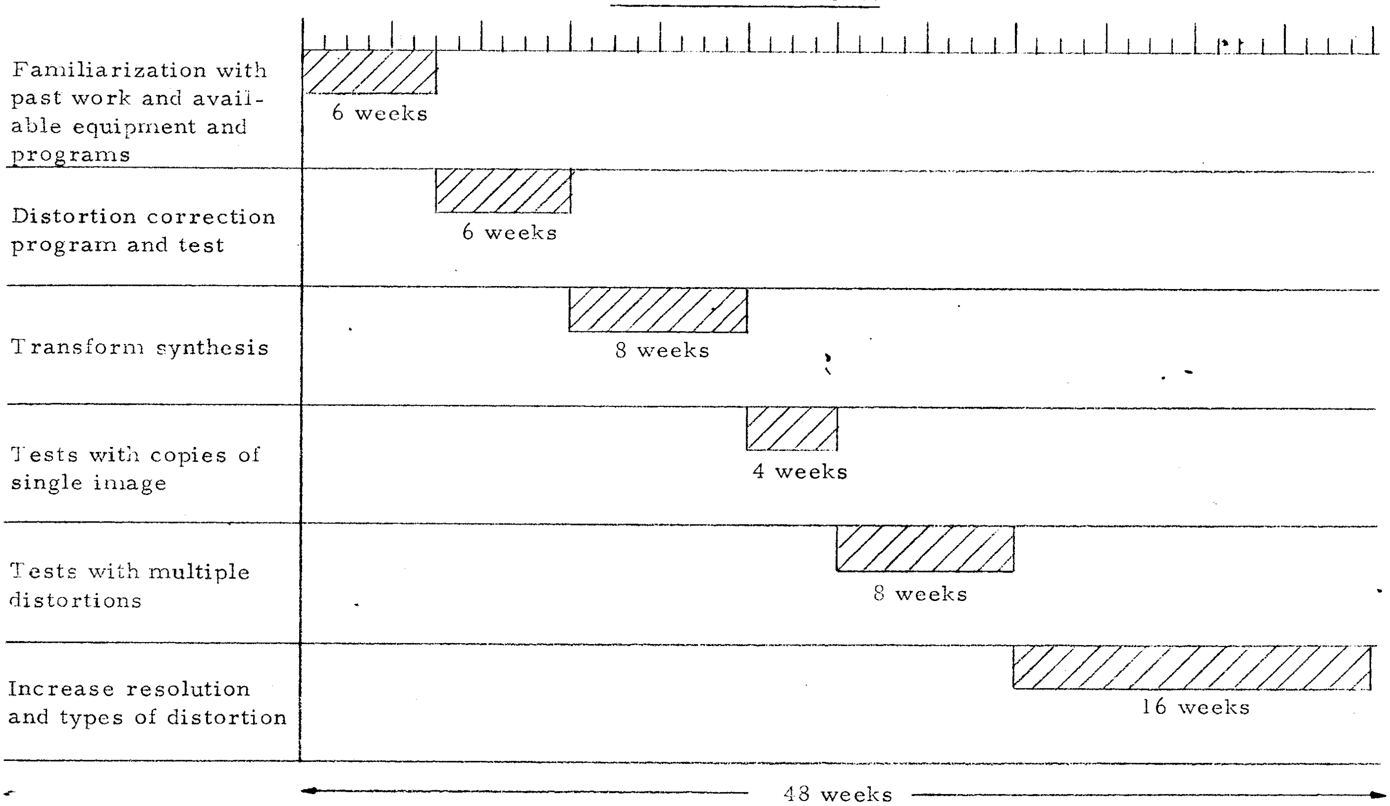
4.0 SCHEDULE

The attached schedule diagram outlines a 48 week program of several phases. The most important milestone occurs at the end of 32 weeks, at which time it is hoped that multiple image integration on real images can be successfully demonstrated. The remaining 16 weeks are to be employed in an effort to increase the information capacity of the programs and to attempt to handle images taken from different points of view. It should be understood that this schedule represents the optimistic case of no serious limitations encountered with the basic approach.

As indicated in the manpower loading chart, the principle effort is carried by an engineer-programmer for the first 32 weeks and this effort is doubled for the last 16 weeks. To back up this effort with theoretical and analytical support, a full time mathematician is included in the program. The program supervision is scheduled at 4 hours per week for the duration of the work and it is expected that an average of two days per week will be required for in-house assistance from other staff members having specialized knowledge such as CDC-3300 programs, or for preparation of image samples and etc.

STAT

TESTING SCHEDULE



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Section 5.0

ALTERNATIVE PROGRAM

5.0 ALTERNATIVE PROGRAM

As an alternative to the above recommendations, it is suggested that the remaining contract funds be directed toward the investigation of problem areas common to the development of the Automated Stereo Scanner and Image Integration. The only such problem areas that have appeared so far are:

1. Analysis and study of the feedback of distortion correction techniques with regard to stability and convergence.
2. A study of the range of magnitude of the various distortion types over which distortion detection and correction techniques can lock-on and operate.

The first of these two problems is, in part, a portion of the program recommended for the first alternative for the future work on this contract. In either instance the PDP-1 computer and scanner would seem to be an ideal test bed for this study.

The study of lock-on range is an extension of a portion of the feedback study with emphasis on determining the avenues by which the lock-on range might be increased.

An extensive study of these two areas could easily be planned, but as in the case of image integration, the value of the resultant work is determined by the calibre and interest of those performing the work.

The value is not necessarily increased by assigning a larger number of people to the program. For this reason we would recommend a 1 to 2 man effort on this alternative, at least initially. We have not prepared a plan of any more detail for this second alternative, rather we intend to soon prepare a more complete research plan on the Stereo Scanning program of which the above studies will be a part.